Example 5a: Composite Allowables Calculation

MAC/GMC 4.0 includes the ability to determine elastic stress and strain allowables for a composite based on the stress and strain allowables for the constituents. The calculations are based on pure elastic concentration analyses in which, through GMC, the global stress or strain is determined that leads to the stress or strain allowable being reached locally. Because the calculated allowables are based on linear elastic calculations, include no residual stresses or damage, and have not been validated experimentally, they should be thought of as estimated values only. The user is strongly cautioned that the estimated allowables should not be interpreted as "design allowables" that are, by definition, certified via extensive comparison with experimental data. The estimated allowables calculated by the code should also be considered non-conservative.

This problem considers a continuous 0.60 fiber volume fraction graphite/epoxy composite represented by the refined 26×26 circular fiber cross-section approximation RUC architecture. No thermal or mechanical loading is applied as the problem is only concerned with the determination of the allowables.

MAC/GMC Input File: `example_5a.mac`

```
MAC/GMC 4.0 Example 5a - RUC allowables calculation
*CONSTITUENTS
  NMATS=2
# -- Graphite fiber
  M=1 CMOD=6 MATID=U MATDB=1
  NTP=2
  TEM=23.,150.
  EA=388.2E3,390.E3
  ET=7.6E3,7.6E3
  NUA=0.41,0.41
  NUT=0.45,0.45
  GA=14.9E3,15.1E3
  ALPA=-0.68E-6,-0.45E-6
  ALPT=9.74E-6,10.34E-6
# -- Epoxy matrix
  M=2 CMOD=6 MATID=U MATDB=1
  NTP=2
  TEM=23.,150.
  EA=3.45E3,3.10E3
  ET=3.45E3,3.10E3
  NUA=0.35,0.35
  NUT=0.35,0.35
  GA=1.278E3,1.148E3
  ALPA=45.E-6,55.E-6
  ALPT=45.E-6,55.E-6
*RUC
  MOD=2 ARCHID=13 VF=0.60 R=1. F=1 M=2
*ALLOWABLES
  NMAT=2
  MAT=1
   S11=3500. S22=91.2  S33=91.2  S23=31.4  S13=134.  S12=134.  COMPR=SAM
   E11=0.009 E22=0.012 E33=0.012 E23=0.012 E13=0.009 E12=0.009 COMPR=SAM
```

```
  MAT=2
   S11=80.    S22=80.    S33=80.    S23=40.    S13=40.    S12=40.    COMPR=SAM
   E11=0.023  E22=0.023  E33=0.023  E23=0.031  E13=0.031  E12=0.031  COMPR=SAM
*PRINT
  NPL=-1
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:

Number of materials:	2	(NMATS=2)
Constitutive models:	Elastic	(CMOD=6)
Materials:	User-defined (Graphite)	(MATID=U)
	User-defined (Epoxy)	(MATID=U)
Material property source:	Read from input file	(MATDB=1)
Material properties:	See Table 4.1	

3) Analysis type (***RUC**) → Repeating Unit Cell Analysis [KM_3]:

Analysis model:	Doubly periodic GMC	(MOD=2)
RUC architecture:	26×26 circular fiber approx., rect. pack	(ARCHID=13)
Fiber volume fraction:	0.60	(VF=0.60)
Unit cell aspect ratio:	1.0 (square pack)	(R=1.0)
Material assignment:	graphite fiber	(F=1)
	epoxy matrix	(M=2)

4) Loading: None

5) Damage and Failure:

a) Stress and strain allowables estimation (***ALLOWABLES**) [KM_5]:

Number of materials:	2	(NMAT=2)
Fiber stress allowables:	σ_{11} = 3500. MPa	(S11=3500.)
(MAT=1)	σ_{22} = 91.2 MPa	(S22=91.2)
	σ_{33} = 91.2 MPa	(S33=91.2)
	σ_{23} = 31.4 MPa	(S23=31.4)
	σ_{13} = 134. MPa	(S13=134.)
	σ_{12} = 134. MPa	(S12=134.)
Fiber strain allowables:	ε_{11} = 0.009	(E11=0.009)
	ε_{22} = 0.012	(E22=0.012)
	ε_{33} = 0.012	(E33=0.012)
	γ_{23} = 0.012	(E23=0.012)
	γ_{13} = 0.009	(E13=0.009)
	γ_{12} = 0.009	(E12=0.009)
Fiber compression flag:	Compression same as tension	(COMPR=SAM)
Matrix stress allowables:	σ_{11} = 80. MPa	(S11=80.)
(MAT=2)	σ_{22} = 80. MPa	(S22=80.)

	σ_{33} = 80. MPa	(S33=80.)
	σ_{23} = 40. MPa	(S23=40.)
	σ_{13} = 40. MPa	(S13=40.)
	σ_{12} = 40. MPa	(S12=40.)
Matrix strain allowables:	ε_{11} = 0.023	(E11=0.023)
	ε_{22} = 0.023	(E22=0.023)
	ε_{33} = 0.023	(E33=0.023)
	γ_{23} = 0.031	(E23=0.031)
	γ_{13} = 0.031	(E13=0.031)
	γ_{12} = 0.031	(E12=0.031)
Matrix compression flag:	Compression same as tension	(COMPR=SAM)

As shown, stress and strain allowables may be specified for one or more materials within the composites. If allowables are specified for some, but not all constituent materials, the materials for which allowables were not specified will be skipped (i.e., not considered in the allowables calculation). Each of the six stress and strain allowable components may be specified for each material. If a particular component is not specified for a particular material, the calculation will skip that component for that material. A compression flag (COMPR) must also be specified for each material. This indicates how compression is handled for that material. COMPR=SAM indicates that the normal compressive allowables are of the same magnitude as the normal tensile allowables, COMPR=OFF indicates that code should not perform compressive allowables calculations, and COMPR=DIF indicates that the normal compressive allowables are of different magnitude than the normal tensile allowables. For this latter case, three compressive allowables may be specified as: SC11= SC22= SC33= and EC11= EC22= EC33= . The actual constituent allowable values employed in this problem are fictitious. For more information on the estimated allowables calculations, see the MAC/GMC 4.0 Keywords Manual Section 5.

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level: -1 (effective properties only) (NPL=-1)

b) x-y plots (***XYPLOT**): None

7) End of file keyword: (***END**)

Results

Results from the estimated allowables calculations are written to the MAC/GMC 4.0 output file:

```
                * ESTIMATED ELASTIC STRESS ALLOWABLES *

     ************************************************************
     ** CAUTION - These allowables have not been validated and  **
     **           are based only on linear elastic calculations **
     ************************************************************

         --- 1st Subcell ---       --- Avg Material ---     - All Subcells -
         ALLOWABLE   CRITICAL      ALLOWABLE   CRITICAL       ALLOWABLE
COMP      STRESS     SUBCELL        STRESS     MATERIAL        STRESS
```

1	0.2112E+04	325	0.2112E+04	1	0.5599E+04
2	0.6808E+02	13	0.8416E+02	1	0.1199E+03
3	0.6808E+02	339	0.8416E+02	1	0.1199E+03
4	0.3140E+02	39	0.3140E+02	1	0.4000E+02
5	0.2489E+02	313	0.5764E+02	2	0.3179E+03
6	0.2489E+02	13	0.5764E+02	2	0.3179E+03
1	-0.2112E+04	325	-0.2112E+04	1	-0.5599E+04
2	-0.6808E+02	13	-0.8416E+02	1	-0.1199E+03
3	-0.6808E+02	339	-0.8416E+02	1	-0.1199E+03

* ESTIMATED ELASTIC STRAIN ALLOWABLES *

****
** CAUTION - These allowables have not been validated and **
** are based only on linear elastic calculations **
****

	--- 1st Subcell ---		--- Avg Material ---		- All Subcells -
COMP	ALLOWABLE STRAIN	CRITICAL SUBCELL	ALLOWABLE STRAIN	CRITICAL MATERIAL	ALLOWABLE STRAIN
1	0.9000E-02	39	0.9000E-02	1	0.2300E-01
2	0.1283E-01	325	0.1417E-01	1	0.2770E-01
3	0.1283E-01	351	0.1417E-01	1	0.2770E-01
4	0.1704E-01	39	0.1704E-01	1	0.2147E-01
5	0.6549E-02	313	0.1517E-01	2	0.8454E-01
6	0.6549E-02	13	0.1517E-01	2	0.8454E-01
1	-0.9000E-02	39	-0.9000E-02	1	-0.2300E-01
2	-0.1283E-01	325	-0.1417E-01	1	-0.2770E-01
3	-0.1283E-01	351	-0.1417E-01	1	-0.2770E-01

NOTE: 1st subcell --> based on 1st subcell reaching specified constituent allowable
Avg material --> based on 1st material whose avg stress/strain reaches allowable
All subcells --> based on all subcells reaching specified constituent allowable

Three sets of results are generated for the estimated composite stress and strain allowables. "1st Subcell" allowables are determined based on any subcell within the RUC reaching the specified allowable value for the material within the subcell. This is the most conservative estimated allowable as, due to stress concentrations, certain subcells may locally reach the allowable at a low global stress or strain level. An intermediate "Avg Material" allowable is determined by finding the global stress or strain at which the average stress or strain for each constituent material reaches the specified allowable for that material. Finally, the most liberal (non-conservative) allowable estimate ("All Subcells") is determined by requiring every subcell within the RUC to reach its allowable stress or strain. For the present example, the composite compressive results are identical (in magnitude) to the tensile results as, for both constituent materials, the compressive allowables are the same as the tensile allowables.

The results from this example problem are presented in graphical form in Figure 5.1 and Figure 5.2. The independent estimated allowable components have been normalized by the corresponding specified fiber allowable values. For comparison, the normalized values specified for the matrix material have been plotted as well. Figure 5.1 and Figure 5.2 clearly show that the average material allowables are bounded by the 1st subcell and all subcells allowables. Further, in all cases, the composite average material allowable falls in between the specified matrix and fiber allowables. This is not the case for the 1st subcell allowable, which falls below both constituent allowables for σ_{22}, σ_{12}, and γ_{12}. Likewise, the all subcells allowable is greater than the allowable for both constituents for σ_{11}, σ_{22}, σ_{12}, ε_{22}, and γ_{12}. Clearly, the all subcells stress allowables are unrealistically high as they require every point in the composite to reach the local allowable stress. Obviously, global failure occurs much sooner in real-world structures after only a few local failures initiate.

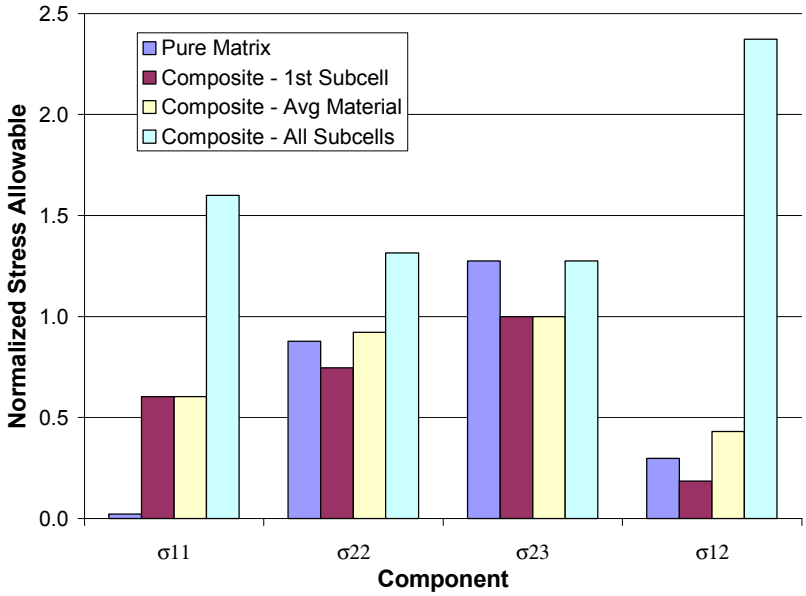

Figure 5.1 Example 5a: Specified matrix and calculated composite stress allowables normalized by the fiber stress allowables for 60% unidirectional graphite/epoxy.

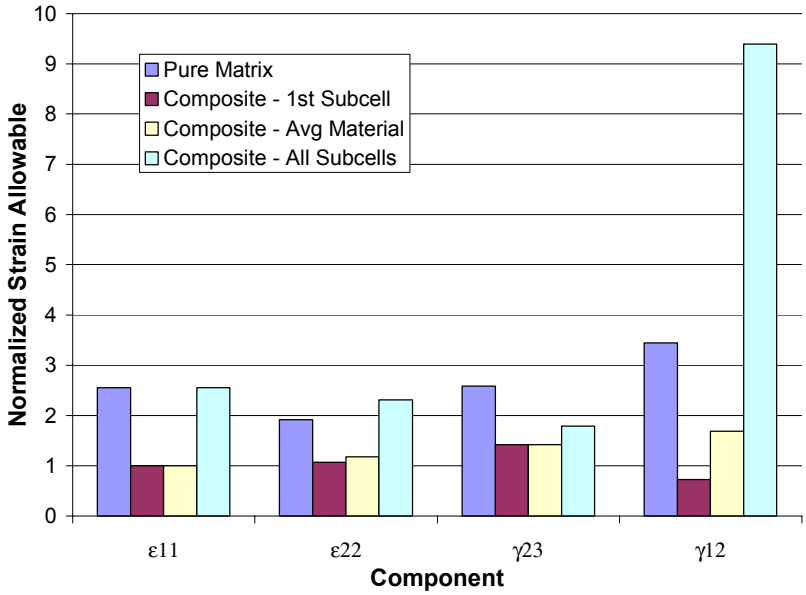

Figure 5.2 Example 5a: Specified matrix and calculated composite strain allowables normalized by the fiber strain allowables for 60% unidirectional graphite/epoxy.